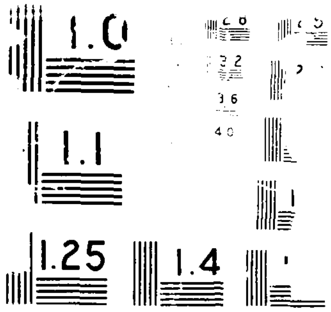
AD-A214 745   AN EXPERIMENTAL AND ANALYTICAL STUDY OF BOUNDARY LAYERS   1/1
IN HIGHLY TURBULE..(U) UNITED TECHNOLOGIES RESEARCH
CENTER EAST HARTFORD CT M F BLAIR MAR 81

UNCLASSIFIED UTRC/R81-914388-18 AFOSR-TR-89-1459   F/G 20/4   NL


1.1
1.25
1.4
3.2
3.6
4.0

AD-A214 745

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE	3. REPORT TYPE AND DATES COVERED
	March 1981	Final (6/1/79-3/31/81

4. TITLE AND SUBTITLE
AN EXPERIMENTAL AND ANALYTICAL STUDY OF BOUNDARY LAYERS IN HIGHLY TURBULENT FREESTREAMS

5. FUNDING NUMBERS
2
61102F
2307/A4

6. AUTHOR(S)
M.F. Blair

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
United Technologies Research Center
Silver Lane
East Hartford, Connecticut 06108

8. PERFORMING ORGANIZATION REPORT NUMBER
AFOSR-TR- 89-1459

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
AFOSR
BLDG 410
BAFB DC 20332-6448

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
F49620-78-C-0064

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release;
distribution unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT (Maximum 200 words)

Under this contract research was conducted to examine two aspects of boundary layer flow: (1) the influence of free-stream turbulence on zero pressure gradient, full turbubulent boundary layer flow; and topic (2) the combined effects of free-stream trubulence and favorable streamwise pressure gradients on transitional boundary layer flow. For topic (1) experimental convective heat transfer coefficients and bounlary layer mean velocity and temperature profile.

14. SUBJECT TERMS	15. NUMBER OF PAGES
	22
	16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
unclassified	unclassified		

NSN 7540-01-280-5500

Standard Form 298 (890104 Draft)
Prescribed by ANSI Std. 239-18
298-01

UNITED TECHNOLOGIES RESEARCH CENTER

UNITED TECHNOLOGIES

East Hartford, Connecticut 06108

R81-914388-18

An Experimental and Analytical Study of Boundary Layers in Highly Turbulent Freestreams

Final Technical Report

Contract No. F-9620-78-C-0064
Project-Task 2307/A4
61102 F

REPORTED BY M. F. Blair

M. F. Blair

M. J. Werle

M. J. Werle

APPROVED BY R. E. Olson

R. E. Olson

DATE March 1981

NO. OF PAGES ____________ COPY NO. ____________

FOREWORD

This report was prepared for the Air Force Office of Scientific Research, United States Air Force by the United Technologies Corporation Research Center, East Hartford, Connecticut, under Contract F49620-78-C-0064, Project Task No. 2307/A4 61102 F. The performance period covered by this report was from 1 June 1978 to 31 March 1981. The project monitors were Col. Robert C. Smith (Ret.), Dr. D. G. Samaras and Dr. James D. Wilson.

The experimental portions of the investigation were conducted in the UTRC Boundary Layer Wind Tunnel. This facility was constructed during 1977 and underwent a series of flow quality evaluation tests during 1978. The UTRC Uniform Heat Flux Flat Wall Model, was also constructed, instrumented, and tested during 1978. Finally, a computer controlled data acquisition system for the UTRC Boundary Layer Wind Tunnel was designed, constructed and made operational during 1978. The construction and evaluation testing of the Boundary Layer Wind Tunnel, Uniform Heat Flux Flat Wall Model, and Data Acquisition system were conducted under UTC Corporate sponsorship.

Contract funded efforts have been devoted to the measurement and analysis of the heat transfer distributions, boundary layer profile and turbulence data discussed in this report.

Dist

A-1

R81-914388-18

An Experimental and Analytical Study of Boundary Layers in Highly Turbulent Free-streams

STATEMENT OF WORK

The Contractor shall furnish scientific effort, together with all related services, facilities, supplies and materials, needed to conduct the following research:

a. For fully turbulent boundary layer flow, convective heat transfer coefficients, boundary layer mean velocity and temperature profiles, wall static pressure distributions, and free-stream turbulence intensity, spectral, and longitudinal integral scale distributions shall be measured using the Contractor's instrumented flat wall installed in the Contractor's Boundary Layer Wind Tunnel. These data shall be obtained with a free-stream turbulence intensity level below 1 percent for two constant free-stream velocities and for three free-stream turbulence levels greater than 1 percent for one constant free-stream velocity (a total of five flow conditions). From these data the integral properties (momentum, displacement, and enthalpy thickness) of the boundary layers will be calculated, and where applicable, the profile data will be reduced to the "universal" coordinates for turbulent boundary layers.

b. The measured heat transfer distributions and turbulent boundary layer profile data obtained under paragraph a above shall be compared to predictions of the UTRC Finite-Difference Boundary Layer deck. The free-stream turbulence energy entrainment calculation procedure currently incorporated in the UTRC deck will be evaluated using these comparisons.

c. For transitional boundary layer flow, convective heat transfer coefficients, boundary layer mean velocity and temperature profiles, wall static pressure distributions, and free-stream turbulence intensity, spectral, and longitudinal integral scale distributions shall be measured using the Contractor's instrumented flat wall installed in the Contractor's Boundary Layer Wind Tunnel. These data shall be obtained for two free-stream acceleration levels with two free-stream turbulence levels each for a total of four flow conditions. From these data, the integral properties (momentum, displacement, and enthalpy thickness) of the boundary layers will be calculated, and, where applicable, the profile data will be reduced to the "universal" coordinates for turbulent boundary layers.

d. The measured heat transfer distributions and transitional boundary layer profile data obtained under paragraph c above shall be compared to prodictions of the UTRC Finite-Difference Boundary Layer deck. The method employed in the UTRC deck to compute transitional boundary layers flows will be evaluated using these comparisons.

INTRODUCTION

Improved techniques for calculating heat transfer coefficient distributions on gas turbine airfoils have been sought by engine manufacturers for the entire history of the industry. These heat transfer distributions must be known so that cooling schemes can be tailored to produce the required metal temperature. Accurate heat transfer predictions are an essential feature of gas turbine design because of the need to maximize performance through minimal use of cooling air and the need to minimize development costs through provision of adequate airfoil cooling on the initial design,

In the design of an airfoil cooling scheme the lack of any required heat transfer distribution information may be compensated for by simply overcooling the component. This overcooling may easily exist since gas turbine thermal design systems are typically not based on fundamental fluid mechanics and heat transfer data and analysis alone but rather are calibrated, or adjusted, to provide agreement with engine experience. Among the more obvious benefits that result from elimination of overcooling are reduced aerodynamic cooling penalties, increased burner and turbine mainstream mass flow rates (i.e., increased power) and potentially reduced cost for the fabrication of the airfoil cooling scheme. Furthermore, without a more complete first-principles understanding there is the likelihood that a designer will unknowingly go beyond the range of validity of the design system calibration. There is, then, a clear requirement for the development of airfoil heat transfer distribution prediction procedures which are based on fundamental fluid mechanics and heat transfer data. The great emphasis placed on the development of accurate boundary layer calculation techniques over the past few years reflects the recognition of these needs.

One particularly important topic in the general context of turbine airfoil convective heat transfer is the influence of the freestream turbulence on both transitional and fully turbulent boundary layer profile development. It has, of course, long been recognized that increasing the freestream turbulence level can cause a forward shift of the laminar to turbulent transition region. This particular phenomenon, the reduction of the boundary layer transition Reynolds number with increased freestream turbulence level, is well documented in the open literature for zero pressure gradient flow and can be accurately predicted with at least one currently available boundary layer prediction scheme. The influence of the freestream turbulence on fully turbulent boundary layers, however, is less certain. A number of investigators have studied the effects of freestream turbulence level on flat wall turbulent boundary layer heat transfer rates and have reported conflicting results. One group of experiments has shown significant effects of the freestream turbulence on heat transfer while a second group has indicated negligible or very small influence. Other experiments which documented the effects of freestream turbulence on boundary layer growth, profile structure, and skin friction distribution consistently reported very large and important influences. The current contract was conducted in order to clarify these contradictions. Both wall heat transfer and detailed boundary layer profile data were obtained for fully turbulent boundary layers for a range of freestream turbulence levels to provide data which will definitively indicate the influence that freestream turbulence level has on fully turbulent boundary layer heat transfer. In addition, these experimental data were employed to evaluate the turbulence entrainment models currently incorporated in an existing boundary layer calculation technique.

As previously discussed, the effects of freestream turbulence on the zero pressure gradient boundary layer transition Reynolds number are well understood. The influence of the freestream turbulence on the transition process becomes considerably less well defined, however, for cases in which the boundary layer is also exposed to a pressure gradient. The net result of the combined influence of turbulence and pressure gradient is dependent upon the sign of the pressure gradient and the relative strength of the two effects. For adverse pressure gradients both the turbulence and the deceleration promote the transition process and in this case the net result is simply to hasten transition. For favorable pressure gradients, however, the flow acceleration acts to stabilize the boundary layer and tends to counteract the effect of the freestream turbulence. This interplay of pressure gradient and turbulence results in at least two effects on the transition process: (1) the location of the onset of transition is influenced and (2) the length and character of the transitional boundary layer flow region may be altered significantly. At the present time, only very limited experimental data documenting these effects are available. To further complicate the matter, much of the currently available data are contradictory making it impossible to assess the relative quality of boundary layer calculation techniques for these flows. For these reasons, as part of the present contract both wall heat transfer and detailed velocity and temperature profile data were obtained for accelerating transitional boundary layer flows exposed to high freestream turbulence levels. These data were utilized to evaluate the current capability of an existing boundary layer calculation procedure to predict boundary layer development with combined favorable pressure gradient and high freestream turbulence levels.

The present contract program provides wall heat transfer and detailed mean boundary layer profile development data required to determine the influence of freestream turbulence level on both fully turbulent and accelerating transitional boundary layers. These data are fundamental in nature and can be employed by both UTRC and other workers in the field of boundary layer computation for evaluation of analytical models. In addition, the contract experiments provide a valuable body of detailed heat transfer and boundary layer profile data directly relevant to the problem predicting heat transfer distributions on gas turbine airfoils. Finally, as mentioned above, the information could result in more accurate blade heat transfer distribution prediction techniques and thereby the more efficient use of blade cooling air.

The contract effort consisted of the documentation and analysis of experimental flat wall boundary layer profile and heat transfer data to determine the influence of freestream turbulence on transitional and fully turbulent boundary layer flows. For fully turbulent, zero pressure gradient boundary layer flows the following data were obtained for a range of freestream turbulence intensities: convective heat transfer coefficients; boundary layer mean velocity and temperature profiles; test wall static pressure distributions and freestream turbulence intensity, spectral and longitudinal integral scale distributions. These same measurements were obtained for various combinations of favorable pressure gradients and freestream turbulence levels for transitional boundary layer flows. From these data the integral properties of the test boundary layers were calculated and, where applicable, the profile data were reduced to the "universal" coordinates for turbulent boundary layers U^+, Y^+ and T^+. Finally, the measured heat transfer distributions and boundary layer profile development were compared to predictions of the UTRC Finite-Difference Boundary Layer Deck. These comparisons were employed to evaluate the computation methods currently incorporated in the UTRC deck.

STATUS OF THE RESEARCH EFFORT

Under this contract, research was conducted to examine two aspects of boundary layer flow: topic (1) the influence of free-stream turbulence on zero pressure gradient, fully turbulent boundary layer flow; and topic (2) the combined effects of free-stream turbulence and favorable streamwise pressure gradient on transitional boundary layer flow.

For topic (1) experimental convective heat transfer coefficients, boundary layer mean velocity and temperature profile data and wall static pressure distribution data were obtained for five flow conditions of constant free-stream velocity and free-stream turbulence intensities ranging from approximately 1/4% to 7%. Free-stream multi-component turbulence intensity, longitudinal integral scale, and spectral distributions were obtained for the various turbulence levels. These data fulfill task "a" of the Statement of Work. In addition, in fulfillment of task "b" of the Statement of Work, comparisons were made between the data of task "a" and prediction of the UTRC Finite-Difference Boundary Layer Deck. A technical report (Ref. 1) "UTRC R80-914388-12, The Influence of Free-Stream Turbulence on the Zero Pressure Gradient Fully Turbulent Boundary Layer" was prepared describing the details of the work conducted for topic (1). Reference 1 contains the following: (1) a complete description of the newly constructed wind tunnel in which these experiments were conducted as well as details of a series of flow quality evaluation tests of the facility, (2) details of the boundary layer and turbulence data acquisition and analysis techniques employed, (3) multi-component free-stream turbulence intensity distributions and longitudinal integral scale and spectral distributions for all flow conditions, (4) Stanton numbers, skin friction coefficients, boundary layer profile and integral property data (momentum, displacement and enthalpy thicknesses) for all flow conditions, (5) an analysis of the experimental results and (6) comparisons of the present experimental results with predictions of the UTRC Finite-Difference Boundary Layer Code. In addition, a data report (Ref. 2 - UTRC R81-914388-15 "Final Data Report-Vol. I - Velocity and Temperature Profile Data for Zero Pressure Gradient, Fully Turbulent Boundary Layers") containing the reduced and plotted profile data for topic (1) was assembled. Numerous data quality checks and measurements to insure data consistency were obtained during the course of this experiment. In addition, for applicable cases, comparisons were made between data obtained in the present program and the results of other workers. This in-depth examination of the present data indicated that they were of extremely high quality and free of anomolies.

Analysis of the data indicates that the heat transfer, skin friction, velocity and temperature mean profile, and free-stream turbulence data form a self-consistent set of information. The following conclusions were reached from the work conducted for topic (1). These conclusions indicate that for gas turbine applications, where free-stream turbulence levels can be extremely high, the influence of the turbulence on the airfoil heat transfer could be significant.

1. For zero pressure gradient, turbulent boundary layer flow, the skin friction coefficient increases with increasing free-stream turbulence level. As an example,

increases of approximately 14% above the low free-stream turbulence skin friction coefficient for the same Re_θ were measured for a turbulence intensity of 7%. (See Fig. 61 of Ref. 1)

2. Heat transfer rates also increased with increasing turbulence level. Stanton numbers measured for a wide range of free-stream turbulence intensities (turbulence intensity increases with increasing grid no.) are presented in Fig. 1a as a function of Re_θ. Turbulence intensity and length scale distributions for these grids are given in Figs. 33 and 37 of Ref. 1 respectively. In addition, Stanton number is given as function of turbulence intensity in Fig. 67 of Ref. 1. An examination of Fig. 1a reveals that for the low free-stream turbulence test case (... no turbulence grid) the present data agreed very well with the predicted heat transfer distribution of Jayatillaka (Ref. 3). In addition it can be seen that the local Stanton number increased progressively with increasing turbulence intensity. As an example, for 5% turbulence intensity the measured heat transfer coefficients were approximately 15% greater than the low free-stream turbulence values (See Fig. 67 of Ref. 1).

3. The Stanton number increased at a somewhat higher rate with increasing free-stream turbulence than did the skin friction. Calculated Reynolds Analogy factors ($2St/C_f$) are presented as a function of free-stream turbulence intensity in Fig. 1b. It can be seen that at low turbulence levels the present data agreed very well with the results of Refs. 4, 5, and 6. A progressive increase of Reynolds Analogy factor with increasing turbulence is evident.

4. Although the above effects are primarily a function of the local free-stream turbulence intensity it has been shown that the turbulence length scale (see Fig. 71 of Ref. 1) and the momentum thickness Reynolds number (for Re_θ < ...), also exert some influence. As examples of these correlations skin friction and heat transfer data from the present study and a number of other investigations are presented as functions of both turbulence and Re_θ in Figs. 2a and 2b.

5. The wake strengths of both the mean velocity and temperature profiles were shown to be significantly depressed with increasing free-stream turbulence. Changes in the skin friction and Stanton numbers have been inferred from these wake depressions using an analysis by P. Bradshaw (Ref. 10). The "wake inferred" changes were shown to be consistent with the "wall inferred" changes discussed in conclusions (1 and 2)

6. The following correlations represented the data obtained in the present program with reasonable accuracy.

a. Influence of turbulence on the skin friction coefficient

$$C_f/C_{f_o}\Big|_{Re_\theta = CONST} = 0.98 + 1.92\left(\frac{Re_\theta}{1000}\right)^{0.4} T$$

b. Influence [illegible] turbulence on heat transfer

$$St/St_0\Big|_{Re_\delta = const} = 0.98 + 2.50 \left(\frac{Re_\delta}{1000}\right)^{0.4} T$$

[illegible]. Influence of turbulence on the Reynolds Analogy Factor

$$2St/C_f = 1.18 + 3T$$

b. The turbulence model of McDonald and Kreskovsky provided a reasonably accurate prediction of free-stream turbulence effects on flat plate skin friction. Predictions of the effects of turbulence on heat transfer are presented in Fig. [illegible]. The predictions are seen to under predict the effect of the turbulence for all Re ranges studied.

For topic (2) experimental convective heat transfer coefficients, boundary layer mean velocity and temperature profile data, and wall static pressure distribution data were obtained for four combinations of streamwise acceleration and free-stream turbulence intensity. Free-stream multi-component turbulence intensity, longitudinal integral length scale, and spectral distribution data were obtained for the four test cases. These data fulfill the requirements of task "c" of the Statement of Work. In addition, in fulfillment of task "d" of the Statement of Work, comparisons were made between the data of task "c" and predictions of the UTRC Finite-Difference Boundary Layer Code. A technical report (Ref. 11 - UTRC R81-914[illegible]-17, "Combined Influence of Free-Stream Turbulence and Favorable Pressure Gradients on Boundary Layer Transition and Heat Transfer") was prepared describing the details of the work conducted for topic (2). Reference 11 contains the following: (1) multi-component free-stream turbulence intensity distributions for all flow conditions; (2) Stanton numbers and boundary layer profile and integral property data (momentum and displacement thicknesses) for all four test cases; [illegible] experimental [illegible] with predictions of the UTRC Finite-Difference Boundary Layer Code. In addition, a data report (Ref. 12 - UTRC R81-914[illegible]-16 "Final Data Report - Vol. II - [illegible] and Temperature [illegible] Data for Ac[illegible], Transitional Boundary Layer[illegible]") containing the [illegible] and plotted profile data for topic (2) was [illegible].

Analysis of the results for topic (2) indicate that the data were accurate and [illegible] and that the experimental boundary layers were highly two-dimensional. The free-stream turbulence distributions generated for these tests were shown to be both homogeneous and nearly [illegible]. It is anticipated that these results will provide a needed set of fundamental, well documented experimental test cases to which analytical boundary layer predictions can be compared. The following results and conclusions emerged from the work conducted for topic (2):

2. Heat transfer distribution measurements were obtained for five free-stream turbulence intensity levels for each of two streamwise accelerations (a total of ten flow conditions). As an example of these data, measured distributions for five turbulence levels with a fixed streamwise acceleration $K = \nu/U_\infty^2 \; dU_\infty/dX$ = 0.20 x 10^{-6} are presented in Fig. 3.

The heat transfer distributions presented in Fig. 3 demonstrate the progressive upstream movement of the transition process with increasing freestream turbulence. For no turbulence grid (T [illegible]) the test boundary layer apparently remained laminar for the entire length of the test section. With increasing turbulence the transition process moved progressively upstream until, for grid 4, transition began about 3 inches from the plate leading edge. The data of Fig. 3 also indicate that, as would be expected from the results of topic (1), for the fully turbulent regions of the various flows the free-stream turbulence level increases the heat transfer.

Heat transfer distribution measurements were also obtained at five levels of free-stream turbulence and a stronger streamwise acceleration $K = \nu/U_\infty^2 \; dU_\infty/dX$ = 0.75 x 10^{-6} (see Fig. 4). For this stronger acceleration level transition was suppressed for the entire test flow length for both the no grid and grid 1 test cases. In addition, for grid 2 installed the length of the transition region was much greater for the more highly accelerated case.

3. Sample velocity profile data obtained for one of the test flow cases (K = 0.2[illegible] x 10^{-6}, grid 2) are presented in Fig. 5. These profile data, presented in the universal turbulent coordinates demonstrate the progressive change from fully laminar to fully turbulent boundary layer flow along the test wall. In Ref. 11 the streamwise distributions of the integral boundary layer thicknesses δ^* and θ are presented for all test flow conditions.

4. Comparisons of the transitional velocity profile shape factor and wall heat transfer distribution data indicate that fully turbulent mean velocity profiles are [illegible] upstream of fully turbulent wall heat transfer rates. The present data [illegible] that the mean velocity profile is established in a shorter length than is required for the development of the equilibrium turbulence distribution.

5. Transition location data obtained in the present program [illegible] very well with data from other flat wall studies for both zero pressure gradient and accelerating flows. Suggested correlation curves are given for prediction of flat wall transition locations with the combined effects of free-stream turbulence and streamwise acceleration.

6. The assessment of the [illegible] Boundary Layer Code indicated that the transitional turbulence model of McDonald-Fish/Kreskovsky provides accurate prediction of transitional boundary layer shape factor for cases with combined pressure graident and free-stream turbulence effects. Heat transfer predictions were found to be less satisfactory.

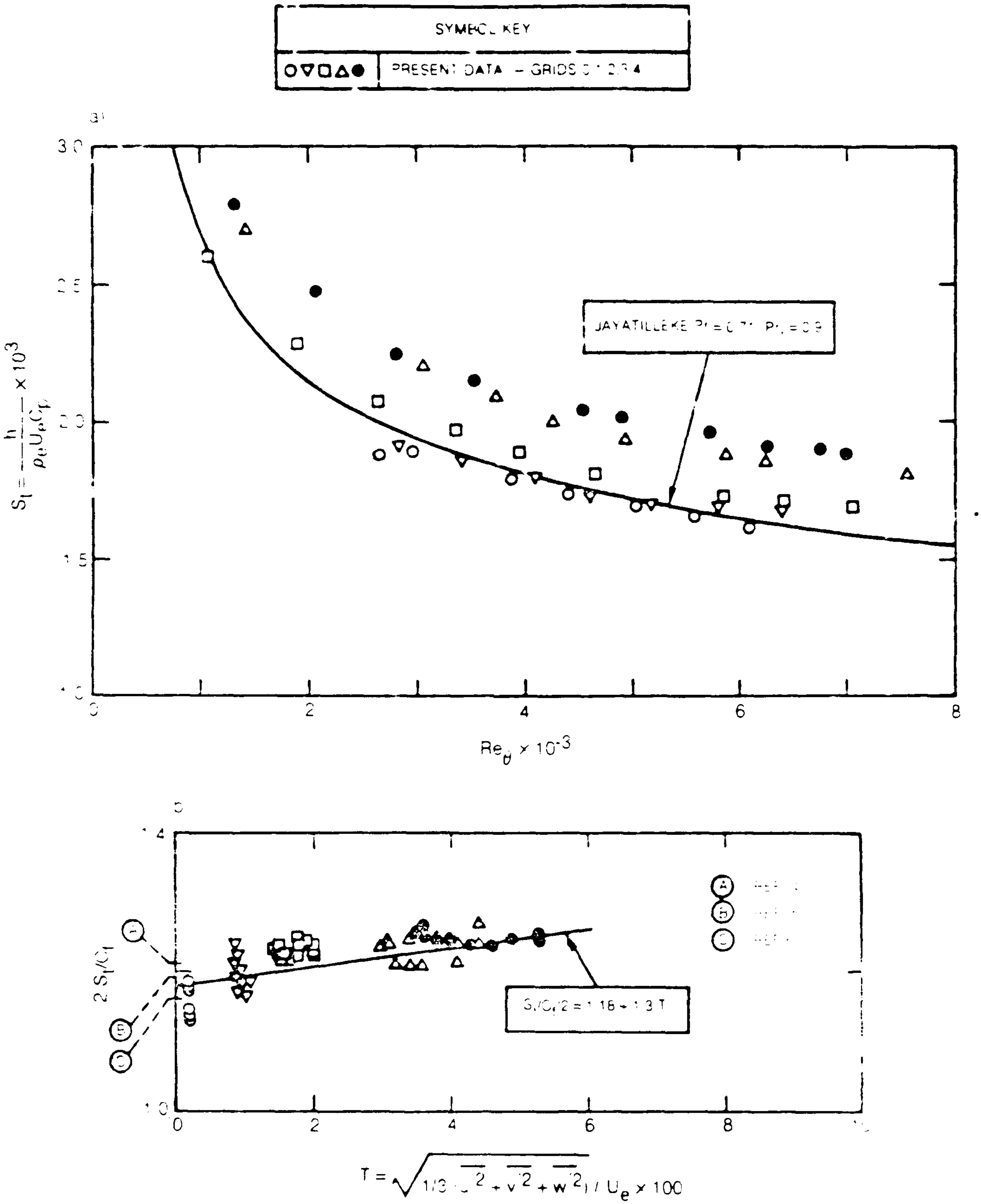


Figure 1. Influence of [illegible] Free-Stream Turbulence on Heat Tran[illegible] and the Reynolds Analogy Factor

SYMBOL	KEY	Re_θ RANGE
▲	HUFFMAN et al (REF. 7)	[illegible]
■	CHARNAY et al (REF. 8)	[illegible]
— — — —	MEIER & KREPLIN CORRELATION (REF. 9)	[illegible]
—··—	SIMONICH & BRADSHAW CORRELATION (REF. 5)	[illegible]
○▽□△●	PRESENT DATA — GRIDS 0 1 2 3 4	[illegible]
- - - - -	THEORETICAL RESULTS (UTRC)	[illegible]
▨	THEORETICAL RESULTS (UTRC)	[illegible]

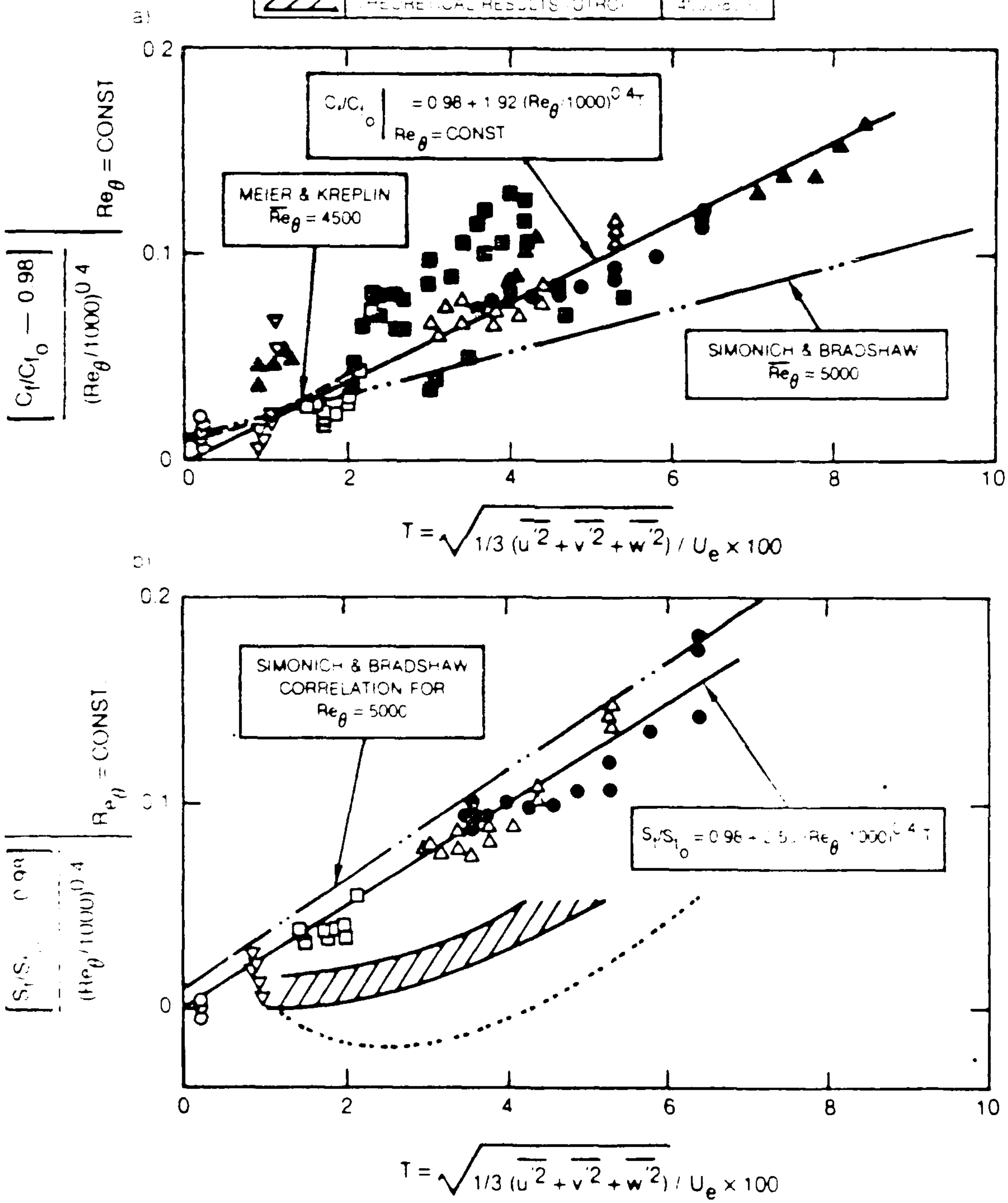


Figure 2. Influence of Free-Stream Turbulence Intensity and Re_θ on Skin Friction and Heat Transfer

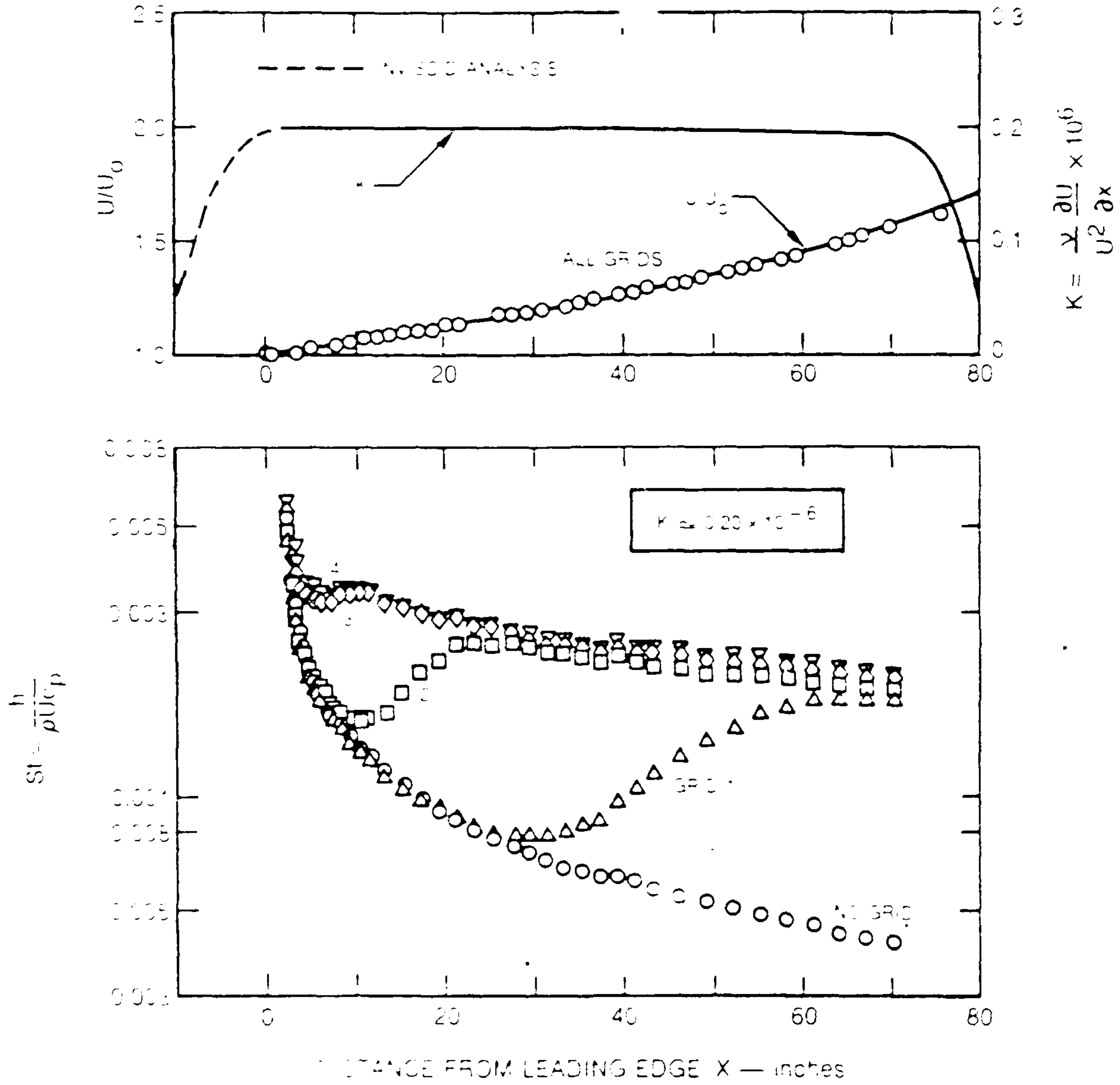


Figure 3: Acceleration and Heat Transfer Distributions for Wedge 1 With 5 Free-Stream Turbulence Levels

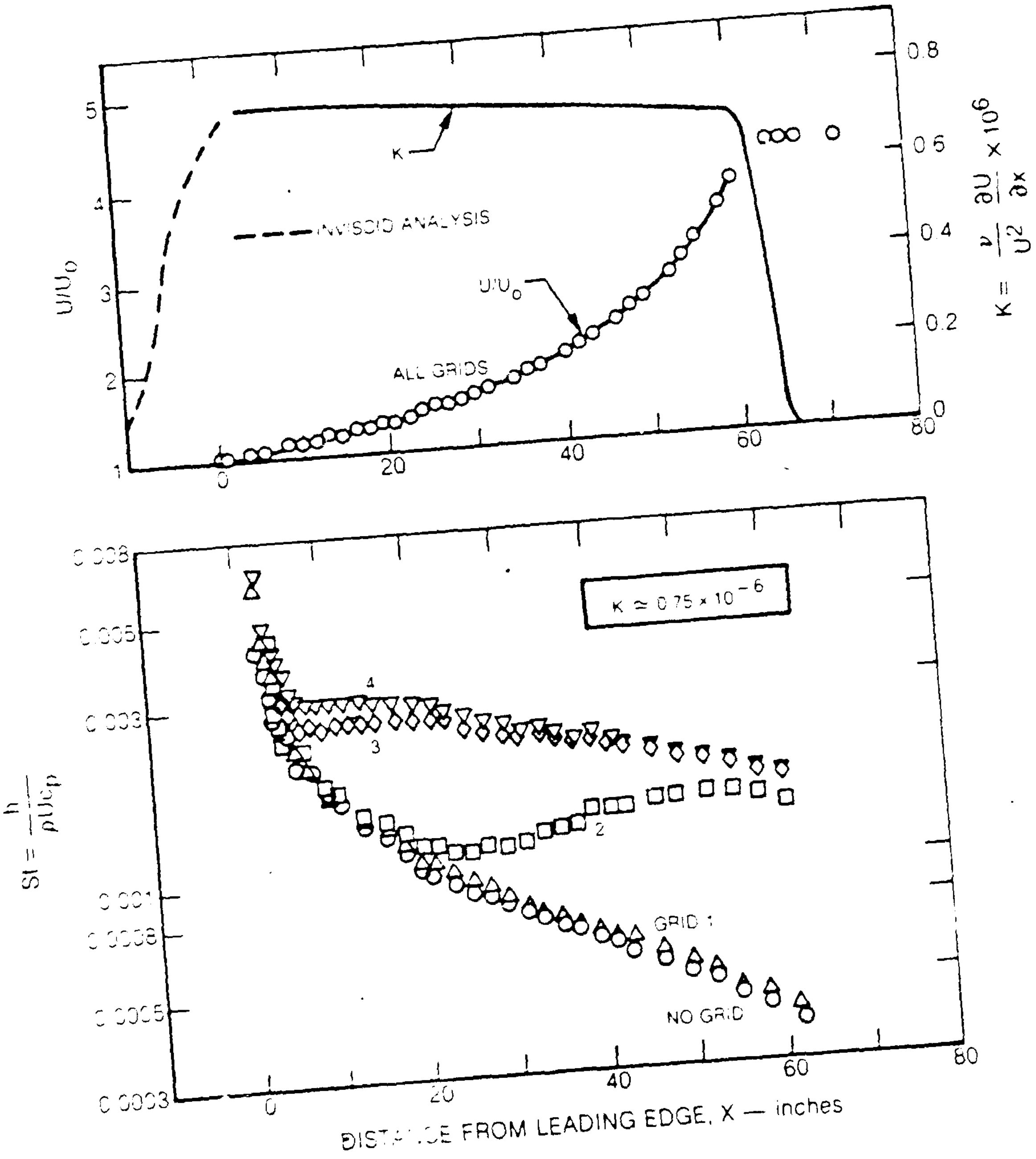


Figure 4: Acceleration and Heat Transfer Distributions For Wedge 2 and 5 Free-Stream Turbulence Levels

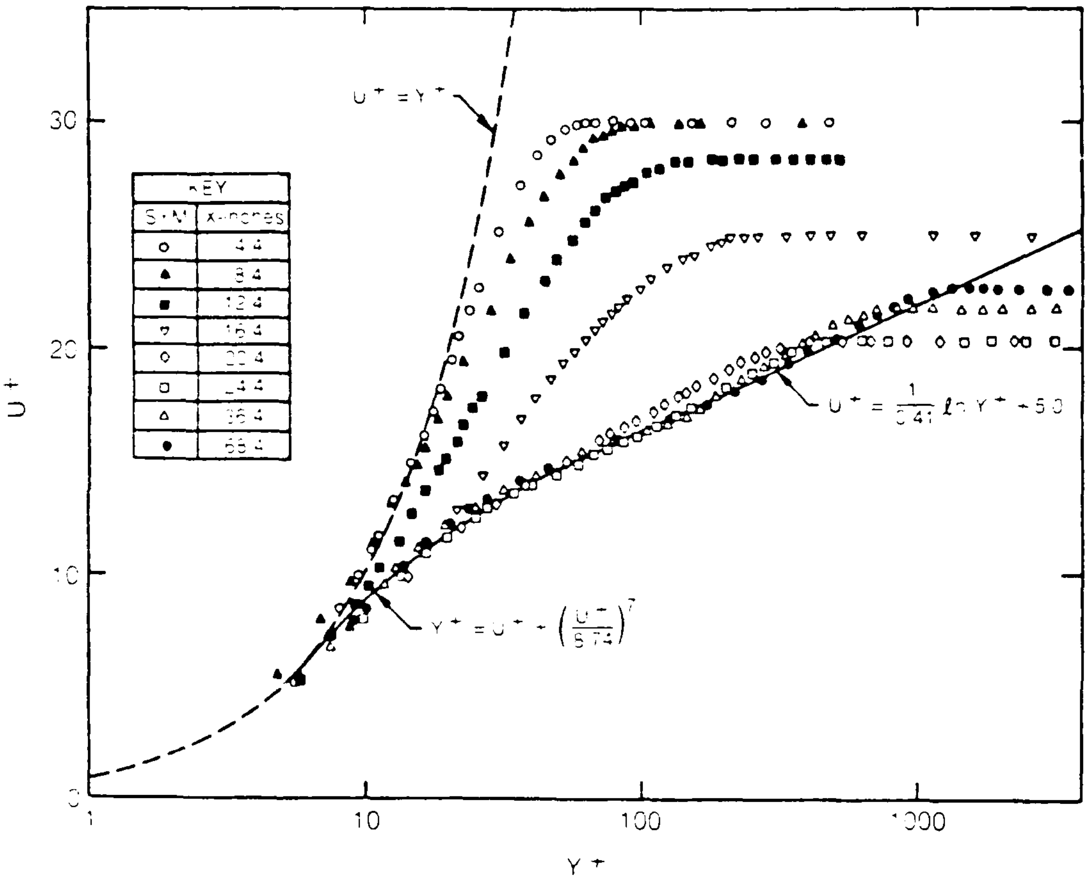


Figure 3: Development of the Mean Velocity Profiles Along the Test Wall For K = 0.20 x 10^{-6} And Grid 2 - Universal Turbulent Coordinates

References

1. Blair, M. F. and M. J. Werle: The Influence of Freestream Turbulence on the Zero Pressure Graident Fully Turbulent Boundary Layer. UTRC Report R80-914-388-12, Sept. 1980.

2. Blair, M. F.: Final Data Report - Vol. I - Velocity and Temperature Profile Data for Zero Pressure Gradient, Fully Tubulent Boundary Layers, UTRC Report R81-914388-15, Jan. 1981.

3. Jayatilleke, C. L. V.: The Influence of Prandtl Number and Surface Roughness on the Resistance of the Laminar Sublayer to Momentum and Heat Transfer, Progress in Heat and Mass Transfer, Vol. 1, Pergamon Press Ltd., London 1969.

4. Spaulding, D. B.: Contribution to the Theory of Heat Transfer Across a Turbulent Boundary Layer, Int. J. Heat and Mass Transfer, Vol. 7, 1964.

5. Simonich, J. C. and P. Bradshaw: Effect of Free-Stream Turbulence on Heat Transfer through a Turbulent Boundary Layer. ASME Journal of Heat Transfer, Vol. 100, No. 4, November 1978.

6. Chi, S. W.: Friction and Heat Transfer in a Compressible Turbulent Boundary Layer on a Smooth Flat Plate, Ph.D. Thesis, Imperial College, University of London, 1965.

7. Huffman, G. D., D. R. Zimmerman, and W. A. Bennet: The Effect of Free-Stream Turbulence Level in Turbulent Boundary Layer Behavior. AGARD AG164, pp. 91-115, 1972.

8. Charnay, G., G. Compte-Bellot, and J. Mathiew: Development of a Turbulent Boundary Layer on a Flat Plate in an External Turbulent Flow, AGARD, CP 93, Paper No. 27, 1971.

9. Meier, H. V. and Kreplin, H. P.: Influence of Freestream Turbulence on Boundary Layer Development. AIAA Journal, Vol. 18, No. 1, January 1980.

10. Bradshaw, P.: Effect of Free-Stream Turbulence on Turbulent Shear Layers. ARC, Paper 35648, 1974.

11. Blair, M. F. and M. J. Werle: Combined Influence of Free-Stream Turbulence and Favorable Pressure Gradients on Boundary Layer Transition and Heat Transfer. UTRC Report R81-914388-17, March 1981.

12. Blair, M. F.: Final Data Report-Vol. II- Velocity and Temperature Profile Data for Accelerating, Transitional Boundary Layers, UTRC Report R81-914388-16, Jan. 1981.

LIST OF WRITTEN PUBLICATIONS

The following papers are currently being prepared for submission to conferences and journals. Copies of thes papers will be sent to AFOSR simultaneously with their submission for publication. Likely titles, authors and journals are as follows:

1. Title - Development of a Large-Scale Wind Tunnel for the Simulation of Turbomachinery Airfoil Boundary Layers.

   Authors - Blair, M. F., Bailey, D. A. and Schlinker, R. H.

   Journal - Presented at 1981 ASME GAS TURBINE CONFERENCE, Houston, Texas, March 1981. Accepted for publication in ASME Journal of Engineering for Power

   Note - Most of the work reported in this paper was funded by United Technologies Corporation. Some data from task "a" of the Statement of Work of the present contract were used to demonstrate the tunnel performance.

2. Title - The Influence of Free-Stream Turbulence on Skin Friction and Heat Transfer for a Turbulent Boundary Layer

   Author - Blair, M. F.

   Journal - ASME Journal of Heat Transfer

3. Title - Combined Influence of Free-Stream Turbulence and Favorable Streamwise Pressure Gradients on Boundary Layer Transition

   Author - Blair, M. F.

   Journal - ASME Journal of Heat Transfer

LIST OF PROFESSIONAL PERSONNEL ASSOCIATED WITH THE RESEARCH EFFORT

Blair, Michael F. - Senior Research Engineer, Gas Turbine Technology Group, Gas Dynamics Section
- Principal Investigator and Project Manager

Dring, Robert P. - Supervisor, Gas Turbine Technology Group,
Gas Dynamics Section

Werle, Michael, J. - Section Chief, Gas Dynamics Section

INTERACTIONS

a. Spoken Papers

1. Title - Influence of Free-Stream Turbulence on Turbulent Boundary Layer Heat Transfer

   Speaker - Blair, M. F.

   Forum - Lehigh University - Mechanical Engineering and Mechanics Seminar

   Date - March 27, 1981

b. Consultive and Advisory functions - Discussions have been held with Professor David Walker of Lehigh University concerning the use of a turbulent boundary layer/pressure gradient data analysis developed by him. Professor Walker's data analysis system was developed under AFOSR funding.

c. Communications with Professor Peter Bradshaw of Imperial College, London, England regarding the subject material of this contract have proved to be extremely useful. Professor Bradshaw has requested that he be kept informed of the progress of our investigation and has provided a number of helpful suggestions concerning the interpretation of our data. A number of papers by himself and theses by his graduate students have proved particularly useful. Professor Bradshaw's expertise in this area is widely recognized. He will serve as data evaluator of the Group II-3 Flow Cases - "Effect of Free-Stream Turbulence on Boundary Layers" for the 1980-81 AFOSR-HTTM-Stanford Conference on Complex Turbulent Flows: Comparison of Computation and Experiment.

LIST OF NEW DISCOVERIES OR PATENTS

No specific new discoveries or patents have resulted from any work conducted under this contract.

Report No. R81-914388-18

INITIAL DISTRIBUTION

DIVISIONAL COPIES

RESEARCH	Copy No.	Location
R. G. Meyerand, Jr.	x	(Text)
W. G. Burwell	x	"
G. F. Hausmann	x	"
F. S. Owen	x	"
C. Gickle, Jr.		
J. W. Clark		
R. J. Bertini, Jr.		
B. Ford		
A. J. DeMaria		
A. S. Kesten		
R. L. O'Brien/Trask		
F. L. VerSnyder		
R. Hooper (Ltr.)	x	
Report Files (2)	x	
I Gould AFPRO-DBA2S	x	(Text)
R. E. Olson	x	"
M. J. Werle	x	"
R. P. Dring	x	"
J. H. Wagner	x	"
M. F. Blair	x	"

END
DATE
FILMED
1-90
DTIC